Experimental and Theoretical Study of Atmospheric Effects through Cosmic ray Muons at Dayalbagh Educational Air Shower Array, Agra

Synopsis

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1. Introduction

The fundamental questions asked in studies of cosmic ray astrophysics since their discovery are: Where do the cosmic rays (CRs) come from? What is their composition? How do they arrive with so much energy? For an answer to these questions, one needs to measure the energy, arrival direction, and primary CRs coming from outer space. CRs are highly energetic charged particles originating from galactic, extragalactic sources and playing an important role in various scientific areas, including space weather, atmospheric studies and climate change **(Maghrabi, A. H. *et. al.* 2023)**.

1.1. Climate Change

Climate change is one of the important studies in the progress towards achieving sustainable development. Climate change studies are a global issue and the United Nations promotes climate change studies under the sustainable development goals of 2030. The study of climate change is a broad area as it involves various aspects but among the many interesting questions in climate change study is that of solar - climate variability which refers to the variations in solar activity and its effects on Earth's climate over a long time scale. These variations can impact the Earth's atmosphere, weather patterns, and climate. The Sun's influence on terrestrial atmospheric dynamics is important; it is driven by the interaction of Earth's solar radiation and orbital motion.

Cosmic ray muons are produced when high-energy cosmic rays from outer space interact with Earth's atmosphere, and have been linked to solar activity and climate change. On Earth, cosmic muon flux measured at ground level is variable and is driven mainly by two phenomena: solar activity in space and modulation due to different meteorological processes in the atmosphere, cosmic radiation in turn, affects various atmospheric and environmental factors. The atmospheric parameters such as temperature and pressure, influence the flux of muons reaching the ground. Two mechanisms of interaction have been discovered in the atmosphere that produce following results published in the literature . In the first mechanism, the air temperature in summer increases which leads to the mass of the air expanding higher means higher pressure, and it follows that the first interactions between primary particles and air molecules occur at a higher elevation. Since muons are produced earlier i.e., their probability of decaying before reaching the ground increases; therefore, the total intensity at sea level is less in summer. This effect is termed as the Blackett effect (Mendonca, R. R. S. *et al.*, 2019).

The second mechanism is based on pion particles, which are responsible for the production of muons; when temperature is higher, air molecules tend to stay apart, and the overall density decreases. At greater elevation with higher temperatures, pions have low probability of encountering matter along their path and tend to decay spontaneously into muons rather than interaction with atmospheric molecules such as nitrogen or oxygen molecules. Therefore, for this process, the production of muons is higher during the summer months, This effect is known as the “Pion effect”. Cosmic ray observatories on the grounds are affected by these periodic variations and the oscillation. Some observatories are more sensitive towards the “Blackett effect”, and some towards the “Pion effect”. Temperature variation may depend on the geographical location and altitude (Arcani, Marco, *et al.*, 2023).

The Sun's approximately 11-year solar activity cycle influences cosmic ray intensity; high solar activity strengthens the solar wind, deflecting cosmic rays and reducing muon production, while low solar activity increases cosmic ray penetration and muon production. The variation in the atmospheric pressure, temperature and relative humidity can cause changes in the Cosmic ray flux observed by the surface detectors and deep underground detectors. (Reply to the comment 2)

GRAPES-3 Experiment (Lat. - 11.4 N, Long. - 76.7 E, 2200 m a.s.l; Ooty, Tamil Nadu, India) : Muon detectors were used to examine fluctuations in cosmic ray intensity and their connections to solar activity and weather conditions. The results revealed a correlation between cosmic ray intensity and factors such as atmospheric pressure, air temperature, and relative humidity, indicating a potential link between solar activity, cosmic rays, and climate (Zuberi, M, *et. al.*, 2024).

IceCube Neutrino Observatory (Lat. - 89. 59 S, Long. - 63. 27 W, 2500 m beneath sea level; Southpole of Antarctica): Although primarily designed detectors to detect neutrinos, IceCube also monitors atmospheric muons, providing data on cosmic ray interactions and atmospheric pressure, temperature for a long timescale to understand climatic effects (Tilav, Serap, *et. al.*, 2019).

Astroparticle Detectors Array (ADA) (Lat. - 41.87 N, Long. - 12.56 E, 538 m a.s.l; Italy): ADA is an educational project aiming to detect cosmic rays and possibly high energy particles known as ultra - high - energy cosmic rays (UHECRs). These are simple detectors spread over entire Italian territory and beyond. ADA has been operating since 2013, they studied the seasonal effect of cosmic ray muons

with respect to atmospheric pressure also linked to the solar activity. (Arcani, Marco, *et al.*, 2023).

In the research conducted by the Ministry of Science, Research and Technology, Tehran (Lat. - 35.70 N, Long. - 51.35 E, 1400 m a.s.l;) (2018) has shown that the simulations and experiments to study the angular distribution of muons and their correlation with atmospheric temperature and pressure. Results indicated that cosmic ray muons could serve as proxies for monitoring environmental parameters and understanding climate dynamics (Bahmanabadi, M., *et. al.*, 2018).

Other studies have proposed that the climate of the Earth could be affected by the changes in cloudiness due to the variations in the cosmic rays intensity in the atmosphere (Belen, B., *et. al*. 2024). This proposal arises from an observed correlation between cosmic ray intensity and cloud cover of the Earth over the period of one solar cycle. The observation has raised the interesting possibility that the cloud interaction of the cosmic rays may explain how a relatively small change in solar activities can produce much larger changes in the climatic conditions of the earth. The physical mechanism has been proposed to explain how cosmic rays could affect the clouds, but they need to be investigated, and the linkage between precipitation periodicities with the solar activities has to be studied methodically.

Hence, the Solar-Climate change studies can be formalised with 10 – 15 year muon data but atmospheric studies of cosmic ray intensity with atmospheric temperature, air pressure, and relative humidity shall be visible with 3 – 4 years data.

1.2. Extensive Air Shower (EAS)

When these highly energetic elementary charged particles bombard the earth and reach the earth's atmosphere these cosmic ray nuclei interact with the other nuclei from the atmosphere, mainly nitrogen nuclei they often produce a cascade of secondary subatomic particles called an Extensive Air Shower (EAS). A cascade of energetic particles, with electromagnetic (EM), muonic, hadronic, and neutrino components. When a primary cosmic ray particle interacts with an atmospheric nitrogen molecule it gives a proton which is a hadron and mesons (charged or uncharged pions, kaons, etc). These pions further decay into muons and neutrinos. The inelasticity of hadronic interactions is 50% mostly pions are produced, neutral pions are responsible for the electromagnetic cascade through an alternate process of pair production, and bremsstrahlung the charged pions and kaons are responsible for the muon and neutrino components **(Riggi, F., 2023)**.

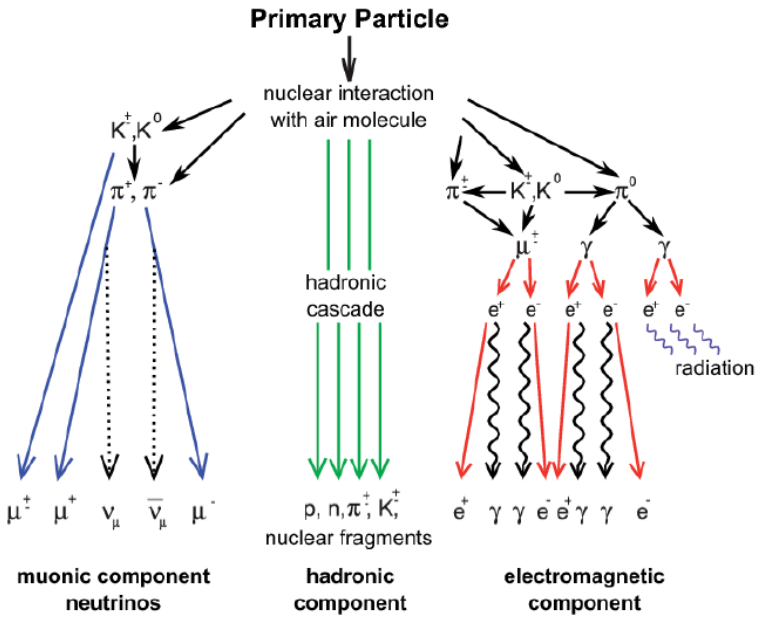

Fig.1. Components of extensive air shower
(Source: Johannes Blumer)

The dominant factor of the primary energy will be transformed into the EM cascade, giving rise to electrons and positrons as the main secondary particles. The secondary particle number increases with shower depth till ionization and Compton scattering begin to dominate for the charged particles. The location of shower maxima varies only logarithmically with primary energy, but the total number of secondaries increases linearly with the primary energy. The origin and acceleration mechanism give important information about the primary cosmic rays. The energy spectrum of primary cosmic rays obeys power law, with a different change in power at two regions: knee and ankle. The knee is the region at 10^{15}eV where the power spectrum index changes from -2.7 to -3.1 approximately.

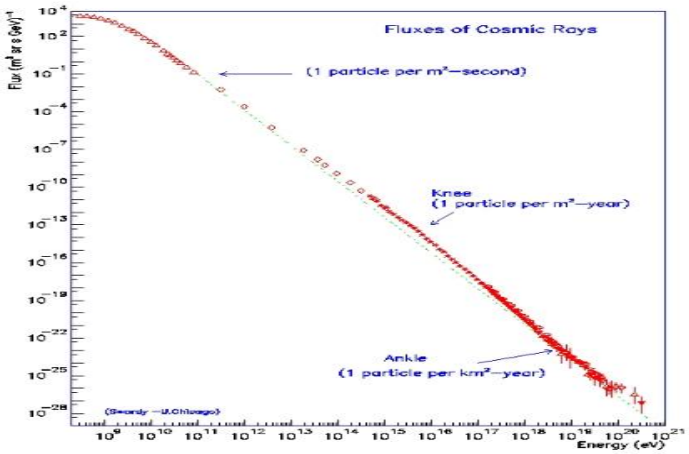

Fig.2. Energy spectrum of cosmic rays
(Source: www.nmdb.eu)

Thus, the indirect measurements of cosmic rays due to their low flux at these energies are studied with ground-based arrays of particle detectors. There are various detection techniques available for indirect measurement, namely particle detectors, air Cherenkov detectors, air fluorescence detectors, radio emission detectors, and acoustic detectors **(Riggi, F., 2023)**.

An air shower gives us a huge amount of information, its energy, and the nature of the primary particles to exploit the properties of energetic hadronic, electromagnetic and leptonic interactions **(Kravka, Antonín, *et. al.*, 2023)**.

a. Longitudinal distribution of the shower has two measurable physical parameters, atmospheric depth at maximum development and particle density at the atmospheric depth.
b. Lateral distribution of the shower has some important parameters such as Arrival direction, core location, shower size, energy, and age determination.

1.3. Dayalbagh Educational Air Shower Array

An indigenously developed ground-based educational mini array shower to study cosmic ray astronomy is installed in the Nuclear Physics Laboratory at Dayalbagh Educational Institute, Agra India (Bhatnagar, S., 2023). This is the first detector in Northern India (Uttar Pradesh) to study cosmic rays. This array is an educational air shower for graduates and scholars to teach them about the highly energetic charged particles near the sea level. These detectors have been located 168 m above sea level with latitude 22.72^{o}N and longitude 78^{o} E.

Muon flux depends upon the height above sea level and the study will be carried out between secondary cosmic ray muons and atmospheric parameters. The air temperature and pressure data is average over the city hence the experimental measurements can be extended to the entire city.

This array consists of 8 plastic scintillation detectors each of area 1m^2 and 2 cm thick.

Fig.3. Dayalbagh Educational Air Shower Array
(Source: K. Garg, S. Bhatnagar, 2021)

These detectors are placed at a distance of 8 m from each other and cover 260 m^2 of area. From these detectors, the signals of secondary cosmic ray particles are obtained because of the scintillation mechanism of plastic scintillation detectors. After every six months, the calibration is done on a regular basis.

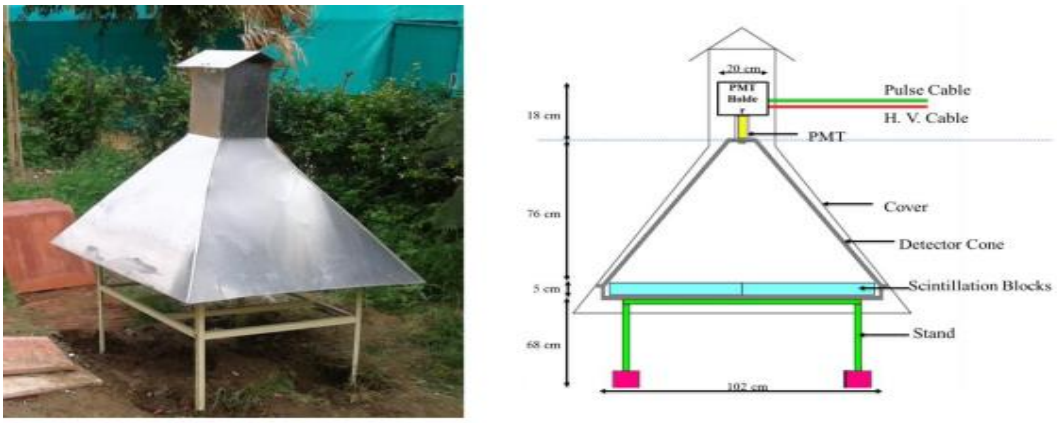

Fig. 4. A schematic diagram of each DEASA detector
(Source: K. Garg, S. Bhatnagar, 2021)

And some other detectors like particle detectors which are widely used for EAS detection and can be made with scintillation, counters, water Cherenkov detectors, and resistive plate chambers. These detectors reconstruct the energy and the arrival of the primary particle by measuring the flux and arrival time of the particles. Large area array-based experiments are KASCADE-Grande in Germany, AGHASA in Japan, Pierre Auger in Argentina, and GRAPES-3 in India.

Air Cherenkov detectors, the basic reconstruction is analogous to the particle detectors, but it contains more information related to longitudinal development of the shower. The relevant data acquired by the air Cherenkov array are the number density, and arrival time of the optical photon. Some experiments are HEGRA in La Palma Island, HESS in Namibia, MACE, Baikal, etc.

Air Fluorescence detectors are a system of telescopes that detect the fluorescence light initiated by extensive air shower due to the excitation and de-excitation of nitrogen molecules as nitrogen is present in abundance, therefore the emitted radiation is mainly composed of UV-light in the range of 290 nm-430 nm. Fly's Eye, telescope-based detectors in Auger, etc.

Radio emission detections are used to detect radio frequency (RF) pulses produced in air shower phenomena. AMANDA and IceCube experiments (located at Antarctica's South Pole) are potent in

detecting radio emissions.

Acoustic effects are also observed in dense homogeneous media, such as water and some extremely energetic and compact showers may have acoustic effects.

1.4. Cosmic ray measurements

One of the most important particles observed in Extensive Air Showers is the muon. According to the standard model of particle physics, muons belong to the leptonic family with a lifetime of $2.2\ \mu s$. The most important primary cosmic rays are proton (P), alpha (α), carbon (C), and Iron (Fe) particles, which are the main sources of atmospheric muons. In fact, the interaction of cosmic rays with air nuclei generates pions, kaons, and muons **(Riggi, F., 2023)**.

The interaction depends on which of the values is greater, the energy of mesons (ϵ), it can be determined by $\epsilon = \frac{h_o mc^2}{c\tau}$, where $h_o = 6.4\ km$, m and τ are the mesons mass and mean lifetime, and c is the speed of light. Interaction is negligible for $E << \epsilon$.

Table 1: This table shows a comparison between Pions and Kaons with rest mass and energy

Particles	Rest Mass	Mean lifetime
Pions	139.57 MeV/c^2	26 ns
Kaons	493.68 MeV/c^2	12 ns

From the given data, one can obtain $\varepsilon_{pions} \simeq 114.56\ GeV$ and $\varepsilon_{kaons} \simeq 850\ GeV$. When charged pions and kaons decay via the weak interaction, muons are created as:

$$\pi^{\pm} \rightarrow \mu^{\pm} + neutrino\ component$$

with 100% probability

$$k^{\pm} \rightarrow \mu^{\pm} + neutrino\ component$$

with 63.5 % probability

Muons present in EAS do not multiply, but gradually lose their energy due to ionization in the atmosphere. The effect of special relativity, muons can penetrate the sea level, rest energy of muons is 105.7 MeV and rest frame lifetime of $2.2\ \mu s$ which are produced at high altitude in the atmosphere,

with time travel to sea level much greater than lifetime in the rest frame of the earth. According to relativity, a muon with energy $E = 2\ GeV$. Hence, the lifetime of the muon, as observed from the earth to be about $42\ \mu s$, permits$2\ GeV$ muons to reach the surface of the earth from the height of 12 km. But muons lose their energy can be represented as:

$$\frac{dE}{dX} \simeq -2\ MeV/gcm^{-2}$$

due to ionization loss in the matter. Thus, muons lose about a few GeV before they reach the sea level with vertical depth $X_v \simeq 1000\ g\ cm^{-2}$. Hence, 3 GeV muons, which have a decay length of 12500 m, are reduced to 6200 m due to energy loss. Consequently, the energy and angular distribution of the muons at each depth of the spectrum, decay, and energy loss in the atmosphere.

Like all charged particles, muons lose energy through coulombic interaction with matter through which they traverse. The average energy loss rate in matter for singly charged particles traveling close to the speed of light is about $2\ MeV/gcm^{-2}$, it can be determined from the Bethe - Bloch equation.

The energy spectrum of primary cosmic rays follows a power law E_{pri}^{-n}. The pions and muons also comply with the same power law, due to energy loss it can be modified. The muon distribution function can be expressed as:

$$\frac{dN(E,\theta)}{dE\ d\Omega} = a(E_\theta + E)^{-n}$$

If the total number of muons be N_0 in all energy range, the value of factor a can be determined as:

$$\alpha = (n-1)(E_\theta + E)^{n-1}$$

Where, E_Z is the energy loss of muons with some inclined direction

The intensity of the muon decreases with increase in zenith angle due to the path length. let assume, the earth surface to be flat for some finite range and detector is placed on the earth surface i.e. observation level. Consider a situation, in which l be the inclined distance travelled by muons, l_0 be the vertical distance travelled by the muons and θ be the zenith angle.

Then, the ratio of integrated intensity of muons at zenith angle θ to the when zenith angle $\theta = 0^0$, so therefore,

$$\frac{\frac{dN}{d\Omega}(\theta)}{\frac{dN}{d\Omega}(\theta = 0)} = \frac{\int_0^\infty (E_\theta + E)^{-n} dE}{\int_0^\infty (E_\theta + E)^{-n} dE} = \left(\frac{E_\theta}{E_0}\right)^{1-n}$$

And from figure,

$$cos\ (\theta) = \frac{l_0}{l}$$

Now combining the above two equations, because of the fact that energy loss of muon is proportional to the path length, therefore

$$\frac{\frac{dN}{d\Omega}(\theta)}{\frac{dN}{d\Omega}(\theta = \theta)} = \left(\frac{E_\theta}{E_0}\right)^{1-n} \alpha \left(\frac{l_0}{l}\right)^{1-n} \approx cos^{n-1}(\theta)$$

so,

$$\frac{dN(\theta)}{d\Omega} \alpha\ cos^{n-1}(\theta) \frac{dN(\theta = 0)}{d\Omega}$$

The muon distribution is usually described by their differential fluxes, the differential flux of cosmic muons can be defined as the number of muons (dN) falling per unit energy (dE) per unit area (dA) per unit time (dt) per unit solid angle ($d\Omega$)

$$F = \frac{dN}{dA.d\Omega.dE.dt}\ (GeV^{-1}cm^2s^{-1}sr^{-1})$$

The definition of flux from the above equation indicates that the sea level differential flux depends upon direction of muon and energy **(Shukla, Prashant and Sunderesh Sankrith *et. al.*, 2018)**. The direction of the cosmic muon can be determined by azimuth angle and zenith angle. The azimuth angle ***φ*** can be defined as the angle between projection of the direction of cosmic muon on X-Y plane, azimuth angle from 0^O to 360^O and the zenith angle is defined as the angle between the z - axis and the direction of incoming cosmic muons.

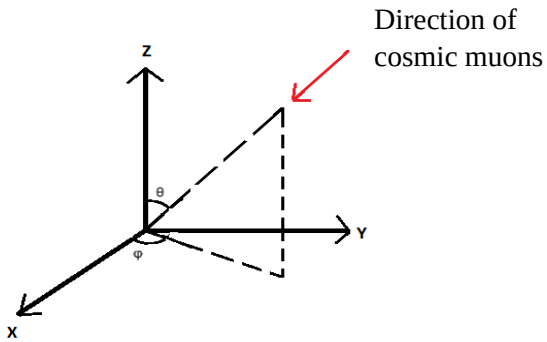

Fig.5. Schematic diagram of muon arrival direction in coordinate axis

The azimuth angle φ can be defined as the angle of projection of the direction of muons on the X-Y

plane and x - axis.

Although the muon distribution at sea level is affected by factors such as solar modulations and geomagnetic fields on azimuth angle φ. These effects are relatively small therefore it can be considered that muon distribution is uniform with azimuth angle. As the thickness of the atmosphere penetrated by the muons increases with zenith angle, the dependence of cosmic muon flux on zenith angle is prominent, especially within low energy. In this range the muon flux varies with $cos^2\theta$. Hence the distribution at sea level flux refers to the differential muon flux with respect to the energy and zenith angle.

There are two ways to obtain the muons distribution at sea level: a.) to derive a parametric model by fitting an empirical method to the measured data of muon flux at sea level; b.) to use Monte Carlo methods to simulate the process of primary CRs incident into the earth's atmosphere and subsequent atmospheric cascade shower and finally obtain the muon flux distribution at sea level.

Shukla and Sankrith in 2018 describe the theoretical and experimental flux values for muon detector located at sea level based on the $cos^2\theta$ mode and implement their own best fit model i.e. $I = I_o D(\theta)^{-(n-1)}$ with $n = 3.09 \pm 0.03$ **(Shukla, Prashant, and Sundresh Sankrith *et. al*, 2018).** Pethuraj in 2017 showed model of muon flux distribution have been obtained at 160 m above sea level presented a best fit model for $I = I_0 cos^2(\theta)$ with $n = 2.00 \pm 0$ and shows a model based on $I(\theta) = p\, cos^2(bq + r) + s$, where p, q and s are constant parameters. The cosine squared model is valid upto zenith angle θ is less than 60^0 **(Pethuraj, S., 2017)**

A semi empirical model based on effective solid angle has been introduced to improve the accuracy in cosmic muon flux distribution at all zenith angles by incorporating the geometrical parameters of detection modules. They assumed that cosmic muon flux not only depends upon only natural factors such as zenith angle, altitude or activities occurring in the heliosphere but also the geometric configuration of the detection modules **(Bae, Junghyun *et. al.*, 2021)**.

Simulations based on CORSIKA to estimate the muon distribution at Tehran level have been done at the height of 1200 m above sea level; the value of n is found out to be 2.30 ± 0.10. They also performed an experiment with muon detectors and the value of n is found to be 2.33 ± 0.11which is a

good match of simulated data with experimental data **(Bahmanabadi M. *et. al.*, 2019)**.

Experimentally these cosmic ray particle measurements had been done using DEASA detectors (Bhatnagar, S. 2020), muon flux, using muon telescope had also been measured **(Bhatnagar, S. 2020).** Other applications of DEASA detectors to space physics and muon tomography have also been explored **(Bhatnagar, S. 2022)**.

2. Challenges

Climate change is an undeniable threat to humanity. It is one of the most important sustainable goals of the United Nations. According to United Nation Goal - 13, the world temperature will exceed 1.5 deg cent. by 2035 and faces a 2.5 deg cent. warming by 2100. Global climate finance flows reached an annual average of $ 803 billion in 2019 - 2020, however developing countries require nearly $ 6 trillion by 2030. The rate of sea - level rise has doubled in the last decade. Highly vulnerable regions experienced 15 times higher mortality rates from disasters compared to very low vulnerability regions (2019-2020).

It is observed that various physical phenomena lead to climate change, like cosmic rays - air shower phenomena, aerosols, carbon gases etc. The shower formation is one of the complex problems in the physical system. The air shower can be understood with the study of hadronic models based on the hadronic interaction that occurs in the atmosphere. This phenomenon can be modelled by Monte Carlo techniques which are based on random generators such as CORSIKA simulation, CRY, FLUKA etc. Based on geographical parameters such as longitude, latitude, altitude and geomagnetic cut-off rigidity.

The real time data measurement 24 x 7 is another challenging task to measure the count rates of secondaries, muons etc. This requires a data acquisition (DAQ) to take daily counts. The demand for low - cost data acquisition is increasing for small-scale detector areas.

The cosmic muons are used to probe environmental parameters such as atmospheric pressure, temperature, and relative humidity as they are sensitive to the environmental parameters and solar activities which relate to climate change.

3. Motivation

The air shower phenomenon occurs due to hadronic cascades, which decay into pions and kaons,

eventually leading to muons. Muon density serves as a crucial observable for studying the relationship between environmental factors such as pressure and temperature. The flux and directional distribution of muons are influenced by the flux and composition of primary cosmic rays. Cosmic muons are valuable for probing environmental parameters like pressure and temperature, as they are sensitive to these factors and solar activities, helping in the study of atmospheric effects. Numerous studies have explored these effects using data from high-energy muon flux measurements at sea level and deep underground experiments such as GRAPES-3, MINOS, and IceCube. These studies have consistently reported a positive temperature coefficient while examining the impact of upper atmospheric temperature variations, although the GRAPES-3 experiment identified a negative dependence for atmospheric muons (Zuberi, M. et al., 2024).

An experiment conducted at an altitude of 2200 meters reported average air shower rates of 1.65 Hz with an RMS of 0.24. The 7-fold coincidence rate was 0.04 Hz with an RMS of 0.02 **(Roy, S. *et al*., 2018).**

Researchers proposed a semi-empirical model based on effective solid angles to improve estimates of cosmic muon intensity at sea level at zenith angles from 0° to 90°. They found that the cosine-squared model had significant errors at high zenith angles above 60°, while the semi-empirical model provided better estimates at all zenith angles. They compared these results with Monte Carlo simulations, experimental normalized count rates, and the cosine-squared model **(Bay. Junghyun *et al.*, 2021).**

A simulated study of millions of extensive air showers (E.A.S.) with 88% protons and 12% alpha particles as primary particles showed that the zenith and azimuth angles of primary particles ranged from 0° to 60° and 0° to 360°, respectively. The simulation studies, conducted at Tehran's level (35°43'N, 51°20'E) at 1200 meters above sea level (a.s.l = 897 g cm^{-2}), used the GHEISHA and UrQMD models for low-energy hadronic interactions and the QGSJET-II model for high-energy interactions. The ratios of muon charge obtained at various angles and energies demonstrated an east-west anisotropy **(Bahmanabadi, M. *et al*., 2019)**.

Simulations of 300,000 extensive air showers with proton, alpha, and carbon particles as primary particles were conducted. The primary energy range was between 1 GeV and 1 PeV, with a differential flux proportional to $E^{-2.7}$ and zenith angles from 0° to 60°. The angular distribution of muons produced

from these showers was obtained **(Bahmanabadi, M. *et al.*, 2018)**.

The zenith angle distribution of muons was determined for different atmospheric depths and energies, achieving a regression of 95%. Using a cosmic muon telescope in Tehran (35°43'N, 51°20'E, 1200 m), the zenith and azimuth angle distributions of atmospheric muons were measured. The minimum energy of muons, determined by energy dissipation in the scintillation counter using the Bethe-Bloch function, was 0.76 GeV. Experimental results showed that the zenith angle distribution of atmospheric muons followed a cosine-powered function, with the mean value of n being 2.33 ± 0.11. Simulation results from the CORSIKA code for air showers generated by proton, alpha, and carbon particles matched well with an n value of 2.30 ± 0.10 **(Bahmanabadi,M. *et al.*, 2018)**.

A collaborative group with INFN Catania and the University of Catania, Italy, conducted the first operational test of a low-cost reconfigurable mini array for cosmic ray detection, designed for educational purposes for Masters and Ph.D. students. This experiment used compact detector arrays capable of detecting lower energy regions of primary particles. Thirty detection modules were arranged in a hexagonal pattern over an area of about 50 m^2. Each module consisted of a (20 cm x 20 cm x 1) cm scintillator tile coupled to a wavelength shifter bar (20 cm x 1 cm x 1 cm) on one side. The Arduino MEGA board was used for electronics, triggering, and data acquisition. The signal from the SiPM was amplified by a trans-impedance amplifier and then sent to the discriminator/TTL shaper module, which provided signal discrimination with an adjustable threshold and shaped the signals into TTL logic signals of about 100 ns. The output signal was read sequentially by the Arduino MEGA board, allowing for long digital readouts. Temperature and pressure sensors (Adafruit sensor Mod. MPL115A2) with a resolution of 0.1°C for temperature and 1.5 hPa for atmospheric pressure were used to study environmental parameters. Data was sent to the Arduino using the I2C protocol, with digital pins 20 (SDA) and 21 (SCL). Digital pins 19 (RX1) and 49 (ICP4) on the Arduino board provided time information from GPS modules, generating an interrupt to synchronize the internal clock with GPS 1PPS (one pulse per second). Typical trigger rates of around 0.05 Hz were observed. Coincidence measurements with multiplicity m3 showed an increase from 3.6 to 6.5. The barometric coefficient for the variation in the shower rate of four-fold coincidence events versus atmospheric pressure was 0.72 ± 0.14% per mbar **(Riggi, F. et al., 2020).**

Sagarika et al. (2018) developed an ARM Cortex-M3-based fast TTL counter that can measure high-rate signals up to 84 MHz from any particle detector. The counter operates at 0 to 3.3 V and includes a programmable timer that can be manually adjusted from 60 seconds to several hours, working in both manual and remote modes. In manual mode, the time interval for count measurement is set by the user, while in remote mode, a LabVIEW program initiates the counter **(Swain, Sagarika, *et. al*,.2018)**.

4. Proposed Objectives

The proposed objectives for the thesis are the following:

- To study the muon interaction at high energy in the Standard Model.
- To experimentally measure cosmic muon flux through DEASA detectors at Agra level (Latitude – 22.22^{O} N, Longitude – 78^{O} E, 170 m above sea level).
- To carry out GEANT 4 simulation of DEASA detectors for muon measurement.
- To undertake simulation studies of an Extensive Air Shower (EAS) using CORSIKA at the Agra level.
- To monitor environmental parameters (such as temperature, pressure, etc) a low - cost Data Acquisition (DAQ) will be set up.
- To study the effects of atmospheric pressure, air temperature, and relative humidity on cosmic ray muons at annual, seasonal, and monthly times scales.

5. Methodology

The methodology for the proposed objectives is as follows:

- Monte Carlo simulation-based models will be used to study the muon interaction at high energy in the standard model.
- Cosmic ray detectors at DEASA will be used to measure the cosmic muon flux at Agra level and compare the results with the theoretical estimation for the flux of cosmic muon based on models like Cosine squared and Semiempirical models etc.
- An algorithm will be designed based on the Hit/Miss Monte Carlo method to estimate the cosmic muon flux for the DEASA. In this method, two detector panels of dimensions (23.5 cm X 24 cm) will simulate and observe the number of hits on both the detectors. Basically, Hit or Miss Monte

Carlo is based on randomly generated points in a bounded graph and counts the number of 'hits' within the specified region using GEANT – 4 simulations (S. Bhatnagar, 2021).

- CORSIKA simulation package will be used to simulate Extensive Air Shower (EAS) and study parameters such as energy distribution of muons, zenith angle distribution, Finding the power index n(X) at atmospheric depth or depth greater than an observation point, muon charge ratio etc.
- The atmospheric effects study will be carried out to investigate the effect of atmospheric pressure, temperature, and relative humidity on cosmic ray muons using 36 months of accumulated observations by Dayalbagh Educational Air Shower Array (DEASA), Agra (Maghrabi, A.H. *et al;* 2023).

For comparative studies of the following groups have been published similar measurements as shown below :

Zuberi, M. et al. GRAPES-3 Collaboration, et al. "Probing atmospheric effects using GRAPES-3 plastic scintillator detectors." *The European Physical Journal C* 84.3 (2024): 255. (Lat. - 11.4 N, Long. - 76.7 E, 2200 m a.s.l; Ooty, Tamil Nadu, India)

Mohanty, P. K., et al. "Fast Fourier transform to measure pressure coefficient of muons in the GRAPES-3 experiment." *Astroparticle Physics* 79 (2016): 23-30. (Lat. - 11.4 N, Long. - 76.7 E, 2200 m a.s.l; Ooty, Tamil Nadu, India)

Maghrabi, Abdullrahman H., Safia A. Alzahrani, and Aied S. Alruhaili. "The Role of Atmospheric Pressure, Temperature, and Humidity on Cosmic Ray Muons at a Low Latitude Station." *International Journal of Astronomy and Astrophysics* 13.3 (2023): 236-258. (Lat. – 21. ·29 N, Long. - 39.15 , 220 m above sea level, King Abdulaziz University, Jeddah, Saudi Arabia)

Arcani, Marco, et al. "The Astroparticle Detectors Array—An Educational Project in Cosmic Ray Physics." *Symmetry* 15.2 (2023): 294 ((Lat. - 41.87 N, Long. - 12.56 E, 538 m a.s.l;, Italy)

6. Expected outcome

The expected outcomes from the proposed work are the following:

- Obtaining the muon flux distribution at AGRA level using DEASA.
- The power index n value will be obtained.
- Low cost – data acquisition will be set up for future experiments.

- The atmospheric effects will be studied from the measured data of cosmic ray muons of 36 months with atmospheric pressure, temperature, and relative humidity.

7. REFERENCES

Aloisio, Roberto. "Ultra-High Energy Cosmic Rays an overview." Journal of Physics: Conference Series. Vol. 2429. No. 1. IOP Publishing, 2023.

Adamson, Phil, et al. "Observation of muon intensity variations by season with the MINOS far detector." *Physical Review D—Particles, Fields, Gravitation, and Cosmology* 81.1 (2010): 012001.

Arcani, Marco, et al. "The Astroparticle Detectors Array—An Educational Project in Cosmic Ray Physics." *Symmetry* 15.2 (2023): 294.

Bae, Junghyun, and Stylianos Chatzidakis. "A new semi-empirical model for cosmic ray muon flux estimation." Progress of Theoretical and Experimental Physics 2022.4 (2022): 043F01.

Bae, Junghyun, Stylianos Chatzidakis, and Robert Bean. "Effective solid angle model and monte carlo method: Improved estimations to measure cosmic muon intensity at sea level in all zenith angles." International Conference on Nuclear Engineering. Vol. 85277. American Society of Mechanical Engineers, 2021.

Bahmanabadi, M. "A method for determining the angular distribution of atmospheric muons using a cosmic ray telescope." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 916 (2019): 1-7.

Bahmanabadi, M., and Leila Rafezi. "Determining the dependence on the energy and atmospheric depth of the angular distribution of muons using the CORSIKA simulation code." Physical Review D 98.10 (2018): 103003.

Bahmanabadi, M., and M. Fazlalizadeh. "Muon charge ratio using the corsika simulation code." Physical Review D 100.8 (2019): 083004.

Belen, B., U. M. Leloğlu, and M. B. Demirköz. "Exploring Relations Between Solar Activity, Cosmic Rays, Clouds and Earth Climate Using Machine Learning Techniques." *Advances in Space Research* (2024).

Bhatnagar, S. (2023). DEASA studies and applications to space physics and muon

tomography. *SciPost Physics Proceedings*, (13), 023.

Bhatnagar, S. 2020, “Muon telescope: An experimental observation of lepton based on coincidence technique”. Journal of Physics: Conference Series, 1804 (2021) 012150, doi:10.1088/1742-6596/1804/1/012150.

S.Bhatnagar, 2020, “Dayalbagh Educational Air Shower Array : Skill based Learning systems”Book Chapter in Aazadi ka Amrit Mahotsav: Community Science Achievements, Opportunities and Challenges, Bluerose Publishers,2023.

Globus, Noémie, and Roger Blandford. "Ultra High Energy Cosmic Ray Source Models: Successes, Challenges and General Predictions." arXiv preprint arXiv:2302.06791 (2023).

Kravka, Antonín, et al. "Reconstruction of the muon production longitudinal profiles in extensive air showers." EPJ Web of Conferences. Vol. 283. EDP Sciences, 2023.

Maghrabi, A. H., Alzahrani, S. A., & Alruhaili, A. S. (2023). The Role of Atmospheric Pressure, Temperature, and Humidity on Cosmic Ray Muons at a Low Latitude Station. *International Journal of Astronomy and Astrophysics*, *13*(3), 236-258.

Mendonça, R. R. S., et al. "Analysis of cosmic rays' atmospheric effects and their relationships to cutoff rigidity and zenith angle using Global Muon Detector Network data." Journal of Geophysical Research: Space Physics 124.12 (2019): 9791-9813.

Pérez Prades, Ona. "The physics of hadron radiotherapy." (2023).

Pethuraj, S., et al. "Measurement of cosmic muon angular distribution and vertical integrated flux by 2 m× 2 m RPC stack at IICHEP-Madurai." Journal of Cosmology and Astroparticle Physics 2017.09 (2017): 021.

Riggi, F. (2023), The Interaction of Primary Cosmic Rays in the Atmosphere. In: Messengers from the Cosmos. UNITEXT for Physics. Springer, Cham. https://doi.org/10.1007/978-3-031-24762-0_6

Riggi, F., et al. "A reconfigurable scintillator-based small array facility for cosmic ray studies." Journal of Physics: Conference Series. Vol. 1561. No. 1. IOP Publishing, 2020.

Roy, S., et al. "Plastic scintillator detector array for detection of cosmic ray air shower." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 936 (2019): 249-251.

Shukla, Prashant, and Sundaresh Sankrith. "Energy and angular distributions of atmospheric muons at the Earth." International Journal of Modern Physics A 33.30 (2018): 1850175.

Su, Ning, et al. "A comparison of muon flux models at sea level for muon imaging and low background experiments." Frontiers in Energy Research 9 (2021): 750159.

Swain, Sagarika, et al. "A TTL Fast Pulse Counter for Detector Signals." Advanced Detectors for Nuclear, High Energy and Astroparticle Physics: Proceedings of ADNHEAP 2017. Springer Singapore, 2018.

Tilav, Serap, et al. "Seasonal variation of atmospheric muons in IceCube." *arXiv preprint arXiv:1909.01406* (2019).

Zuberi, M. et al. GRAPES-3 Collaboration, et al. "Probing atmospheric effects using GRAPES-3 plastic scintillator detectors." *The European Physical Journal C* 84.3 (2024): 255.